Some further remarks regarding scattering of an acoustic wave by a vibrating surface

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An earlier letter to the editor [Piquette and Van Buren, J. Acoust. Soc. Am. **79**, 179–180 (1986)] commented on an article by D. Censor [J. Acoust. Soc. Am. **76**, 1527–1534 (1984)]. In his reply [J. Acoust. Soc. Am. **79**, 181–182 (1986)], Censor made some observations that warrant further comment. The present letter considers in detail plane-wave scattering by a vibrating plane and thereby demonstrates analytically that Censor's theory predicts sum and difference frequency component waves that are of the order of magnitude of pseudosound. This example also illustrates that the parametrically growing sum and difference frequency component waves generated nonlinearly overwhelm those predicted by the Censor theory within a fraction of a wavelength of the scatterer's surface.

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Recently, we published a letter to the editor[1] which commented on an article[2] published by D. Censor. In his reply,[3] Censor made several points which we believe require further comment.

Censor's remarks[3] seem to imply that we are denying the existence of the Doppler effect in acoustics. Censor[3] has pointed out that the Doppler effect has previously been questioned by Petzval. Petzval's objections were resolved by Mach (see reference in Tolman[4]). Unfortunately, Petzval's objections (and Mach's subsequent discussion) appear to bear little relation to the questions we have raised[1] in regard to Censor's work.[2] According to Tolman's summary,[4] Petzval denied the existence of the Doppler effect, claiming that the transmitted frequency of a source equals the received frequency regardless of the physical properties of the medium, provided that the continuity condition is satisfied at all points at rest with respect to the source, and provided that all particles of the medium have identical velocity vectors. We agree with Mach's conclusion that Petzval's argument is generally invalid. Our arguments concerning Censor's work in no way contradict the existence of a frequency change due to a relative motion between source and observer.

We agree that additional frequency components are generated by the scattering of an acoustic wave by a vibrating surface via the Doppler effect. However, we have shown[5,6] that such additional frequency components are also generated by the nonlinear interaction of the primary waves in the fluid surrounding the scattering surface and that, in general, the waves generated by the nonlinear effect overwhelm those generated by the Doppler mechanism within a fraction of a wavelength of the scatterer's surface.

We wish to emphasize once again that we do not question the validity of Censor's work in the area of electromagnetism. Maxwell's equations are strictly linear, and nonlinear effects enter electromagnetic calculations only through the constitutive relations. For most media the constitutive relations for electromagnetism are linear or essentially so, and nonlinear effects are negligible. However, the fundamental equations of acoustics that correspond to Maxwell's equations in electromagnetism (i.e., the equations of continuity and momentum conservation) are intrinsically nonlinear. *In addition,* all fluid media are nonlinear through their constitutive relations; i.e., pressure is a nonlinear function of condensation. Most fluids, such as water and air, are significantly nonlinear. The combined effects of these two sources of nonlinearity in acoustics can produce significant contributions to sum and difference frequency components through mixing during propagation of multifrequency waves. Also in acoustics, a vibrating boundary is a radiator of sound, thereby producing a wave at the frequency of motion of the boundary which then interacts with the incident and reflected waves. There is no such radiation effect in the electromagnetic case (assuming the boundary is uncharged).

We have previously stated[1,5] that Censor's theory predicts results that are of the same order of magnitude as pseudosound. Pseudosound is an effect that arises due to the uncertainty in the motion of the acoustic sensor. A sensor that moves freely with the particles of the medium measures in the Lagrangian frame of reference. A sensor that is fixed in space measures in the Eulerian frame of reference. Acoustic problems solved in either reference frame give equivalent results to first order in Mach number. (Here, Mach number is taken to be the ratio of the maximum speed of the particles of the medium to the speed of acoustic waves of infinitesimal amplitude.) However, the predicted results differ to second and higher order in Mach number. Since it is unlikely that one knows the state of motion of one's sensor sufficiently accurately to distinguish to what extent it moves freely with the fluid (and thus measures in the Lagrangian frame) or to what extent it remains fixed (and thus measures in the Eulerian frame), pseudosecond must be considered to be the practical lower limit of the measurability of acoustic quantities. Censor's theory predicts sum and difference frequency component waves that are of the order of magnitude of pseudosound.

Consider a simple quantitative example: the scattering of a normally incident sinusoidal plane wave (of angular

frequency ω) from an infinite plane vibrating uniformly and harmonically (at angular frequency Ω). (This case has been considered in detail elsewhere.[6]) In order to demonstrate that Censor's theory predicts results that are of the order of pseudosound, we will solve this problem in Lagrangian coordinates assuming that the linear wave equation is exact. We will then transform this solution into Eulerian coordinates. Next, we will compare the transformed solution with that computed using Censor's theory.

Censor has chosen to solve the problem of the scattering of an acoustic wave by a vibrating obstacle in the Eulerian (spatial) reference frame. The incident plane wave in Eulerian coordinates is given by $P^E(x,t) = P_0 e^{i\omega(x/c + t)}$. We turn off all nonlinearities so that the linear wave equation applies. The displacement of the plane is described by the function $\xi(0,t) = \epsilon \sin(\Omega t)$. Applying Censor's theory to this situation, we obtain the following expression for the sum and difference frequency pressure components:

$$P_\pm = \frac{P_0 P_r}{\rho_0 c^2 \Omega} |\omega_\pm| e^{-i(\omega_\pm)(x/c - t)}, \qquad (1)$$

where $P_r = i\rho_0 c \Omega \epsilon$ = pressure amplitude of the directly radiated wave, ρ_0 = fluid density, c = infinitesimal amplitude wave speed, and $\omega_\pm = \Omega \pm \omega$.

Next, we consider the same problem in Lagrangian coordinates. In this case the incident wave is given by $P^L(a,t) = P_0 e^{i\omega(a/c + t)}$. Since the boundary is fixed relative to a Lagrangian frame of reference, the incident wave reflects as from a rigid body giving a reflected pressure $P_0 e^{-i\omega(a/c - t)}$. The radiation from the moving boundary provides a pressure wave $P_r e^{-i\Omega(a/c - t)}$. These two waves travel without interaction when the nonlinearities are turned off. Thus, no sum and difference frequency components are present in the solution obtained in a Lagrangian frame of reference. However, sum and difference frequency components arise if we transform the solution into Eulerian coordinates. An arbitrary Eulerian function $f^E(x,t)$ is transformed into the associated Lagrangian function $f^L(a,t)$ using the expansion[7]

$$\begin{aligned} f^L(a,t) &= f^E(x,t)|_{x = a + \xi(a,t)} \\ &= f^E(x,t)|_{x=a} + \left.\frac{\partial f^E(x,t)}{\partial x}\right|_{x=a} \xi(a,t) + \cdots, \end{aligned}$$

where a = Lagrangian coordinate, x = Eulerian coordinate, and ξ = displacement (common to both systems). Applying this transformation to the Lagrangian scattered wave $P_0 e^{i\omega(a/c - t)}$ we obtain the following expression (accurate to second-order Mach number) for the sum and difference frequency pressure components that arise in the Eulerian reference frame:

$$P_\pm = \frac{P_0 P_r}{\rho_0 c^2 \Omega} \omega e^{-i(\omega_\pm)(x/c - t)}. \qquad (2)$$

Note that since $P_\pm$ is zero in Lagrangian coordinates when the nonlinearities are turned off, Eq. (2) represents pseudosound. The pressure represented by Eq. (2) would only be measured by an acoustic sensor fixed in space (i.e., in an Eulerian frame), and only if the nonlinearities are turned off. Since any real acoustic sensor must move with the molecules of the fluid to some extent, the pressure given by Eq. (2) would never be measured by such a sensor even assuming the linear wave equation to be exact. Any real acoustic sensor in such a situation would measure a pressure between zero and that given by Eq. (2), due to the uncertainty in the hydrophone's motion.

Comparing Eq. (1) (the solution using Censor's theory) to Eq. (2) (which results from merely transforming the monofrequency rigid-body scattered wave from Lagrangian to Eulerian coordinates and retaining only the sum and difference frequency components), we see that they are clearly of the same order of magnitude (differing only in that ω now appears in the coefficient in place of $\omega_\pm$). Thus the effect predicted by Censor's theory arises essentially from the transformation between coordinates and not from medium nonlinearities. An acoustic sensor measuring in the Lagrangian frame, i.e., moving with the fluid, would not detect sum and difference frequency components arising from the effect Censor predicts. An acoustic sensor measuring in the Eulerian frame, i.e., fixed in space, would detect a signal due to Censor's effect but this signal would usually be substantially smaller than that arising from nonlinearities.

Now consider this problem from the point of view of solving the nonlinear wave equation. The sum and difference frequency components arising from nonlinearities for plane-wave scattering from a vibrating plane are obtained in Ref. 6. These can be approximated by

$$P_\pm \approx \left(\frac{(1+\gamma)P_0 P_r}{4\rho_0 c^3}\right) |\omega_\pm| x e^{-i(\omega_\pm)(x/c - t)}, \qquad (3)$$

where γ is the one-dimensional nonlinearity parameter, $1 + B/A$.

Note in Eq. (3) the presence of the distance factor x, characteristic of parametric sources, in the coefficient preceding the complex exponential function. This distance factor causes the nonlinearly generated signal to increase in amplitude with increasing propagation distance. The energy required for this parametric increase in amplitude of the sum and difference frequency component waves is provided by an energy drain from the primary waves. Equation (3), obtained via a perturbation solution, remains valid as long as the energy densities of the secondary waves remain small relative to the energy densities of the primary waves. (See Ref. 6 for a more complete discussion of this.)

It is clear from comparing Eqs. (1) and (3) that the nonlinearly generated signal will become greater than that generated by Censor's Doppler mechanism at some propagation distance. We demonstrate below that this propagation distance is always a fraction of the longest wavelength involved in the problem. The distance factor x of Eq. (3) arises because every element of fluid between the scatterer's surface and the observation point acts as a source of sum and difference frequency waves.[5] Thus the greater the propagation distance, the greater the volume of fluid between the scatterer and the observation point and, generally, the greater is the amplitude of the nonlinearly generated signal Note that the solution to the nonlinear wave equation does not simply produce a "small correction" to the solution based on the linear wave equation, as might be expected, but rather predicts sum and difference frequency components

that rapidly grow to a significant amplitude. Such a possibility exists whenever two primary waves of differing frequency are simultaneously present in a fluid. The parametric growth of the nonlinearly generated sum and difference frequency component waves generally occurs whenever there is a significant "collimation region," i.e., whenever there is a significant volume of fluid through which the wave vectors of the primary waves point in the same direction.

When we compare the nonlinear volume effect solution for the sum and difference frequency components, given by Eq. (3), to the solution for these components resulting from the boundary Doppler effect predicted by Censor, given by Eq. (1), we obtain

$$\frac{[P_\pm]_{\text{Censor surface}}}{[P_\pm]_{\text{nonlinear volume}}} \approx \frac{4c}{\Omega(1+\gamma)x}. \tag{4}$$

For a planar surface frequency of 100 kHz, in a water medium, the two effects become equal at a distance x on the order of 0.14 cm. One should not be disturbed by the presence of the Ω term in the denominator of the ratio in Eq. (4). In the case of low Ω, the relevant factor to scale the distance is the wavelength associated with Ω, which is $2\pi c/\Omega$. Hence, if we let $x = d(2\pi c/\Omega)$, we can determine the fraction d of a wavelength at which the nonlinear volume effect overtakes Censor's surface effect. This occurs for $x = 0.09\ (2\pi c/\Omega)$. Therefore, even in the limiting case in which the frequency of vibration of the planar surface approaches zero (maximizing Censor's boundary effect relative to the nonlinear volume effect), the sum and difference-frequency pressure components generated by nonlinear volume effects exceed those produced by the boundary effect within a propagation distance less than the longest wavelength involved in the problem. Thus, as previously mentioned, we do not deny the existence of the new spectral components generated by the Doppler mechanism cited by Censor. It is simply that the amplitudes of the frequency components generated by this mechanism are generally much smaller than those generated by the nonlinear mechanism. Note that the frequency components created by the Doppler effect are extremely small in the present case due to the *oscillatory* nature of the motion of the vibrating boundary. If the boundary were instead moving with *constant* velocity, the familiar and much stronger Doppler-shifted reflected wave would be obtained.

Since Censor's theory predicts results that are of the order of magnitude of pseudosound, his theory would not be very useful in monitoring the motion of vibrating boundaries even if an experimental arrangement were devised that was unfavorable to the parametric growth of sum and difference frequency component waves generated by the nonlinear mechanism. (Such a possibility arises, for example, if the incident plane wave in the problem discussed above arrives at non-normal incidence.) As previously mentioned, the uncertainty in the motion of a real acoustic sensor is sufficient to inhibit the meaningful measurement of acoustic quantities predicted to be of the order of magnitude of pseudosound.

In his reply[3] to our comments,[1] Censor suggests using a perforated scatterer in an attempt to create a situation which enhances the Doppler mechanism over the nonlinear mechanism for generating sum and difference frequency pressure waves. We have argued[1,5] that since both theories depend on the Mach number in the same way, any change in the parameters of the problem would change the predicted values of each theory by the same factor. (This fact was originally noted by Rogers.[8]) Censor states[3] that such perforations would eliminate the displacement of the surrounding fluid caused by the vibrating boundary. However, if the displacement were to entirely vanish, the quantity P_r of Eqs. (1) and (3) would become zero, and thus both theories would predict null results. Of course, such perforations would not entirely eliminate the radiated wave. While an exact solution for this problem would require re-solving both theories for the perforated surface involved, it is possible to obtain approximate solutions for each theory by slightly modifying Eqs. (1) and (3). This is possible if the perforation diameters and spacings are sufficiently dissimilar from either primary wavelength (thus avoiding linear diffraction phenomena). The primary waves are essentially affected in two ways by using a perforated scatterer: (i) The amplitude of the primary scattered wave of angular frequency ω and, (ii) the amplitude of the directly radiated primary wave of angular frequency Ω, are reduced. Although the amplitude of the incident plane wave of angular frequency ω is not affected, this primary wave produces very little contribution to the sum and difference frequency component waves generated by the nonlinear mechanism, due to the unfavorable propagation direction of this wave relative to the directly radiated wave of angular frequency Ω. In fact, Eq. (3) (which is only approximate) omits the small contribution to the nonlinear field due to direct interaction of the incident wave with the radiated wave, and only accounts for the interaction of the linearly scattered wave with the directly radiated wave. (The complete solution is given in Ref. 6.) We can account approximately for the influence of the perforations on the primary scattered wave by adjusting the quantity P_0 appropriately. Similarly, we can account approximately for the influence of the perforations on the directly radiated wave by adjusting the quantity P_r appropriately. However, note that the quantity $P_\pm$, as computed using the Censor theory, given by Eq. (1), depends on the quantities P_0 and P_r in exactly the same way as the expression for $P_\pm$ derived using nonlinear theory, given by Eq. (3). Thus both computed quantities change by the same factor if the vibrating plane is perforated. This means that the *ratio* of the computed values, given by Eq. (4), is unaffected by the presence of perforations in the scattering surface.

We agree with the final observation Censor made in his reply[3] to our original letter.[1] The experiment we performed[5] could be improved if an arrangement were possible that produced sufficiently wide nulls in the primary field to reduce the degrading effect of hydrophone self-nonlinearity on the measurements. (We were unable to devise an experimental arrangement to achieve this.) However, as previously mentioned, the meaningful measurement of sum and difference frequency waves predicted to be only of the order of magnitude of pseudosound, as is the case with Censor's theory, would not be practical even using a completely linear hydrophone. Since the Censor theory predicts results that are of the order of magnitude of pseudosound, as we have demon-

strated above and elsewhere,[5,6] we conclude that his theory is not very useful for monitoring the motion of moving boundaries in the acoustical case.

[1] J. C. Piquette and A. L. Van Buren, "Comments on 'Harmonic and transient scattering from time varying obstacles [J. Acoust. Soc. Am. 76, 1527–1534 (1984)],' " J. Acoust. Soc. Am. 79, 179–180 (1986).

[2] D. Censor, "Harmonic and transient scattering from time varying obstacles," J. Acoust. Soc. Am. 76, 1527–1534 (1984).

[3] D. Censor, "Reply to 'Comments on Harmonic and transient scattering from time varying obstacles [J. Acoust. Soc. Am. 76, 1527–1534 (1984)],' " J. Acoust. Soc. Am. 79, 181–182 (1986).

[4] K. Tolman, "Christian Doppler and the Doppler Effect," Eos 65, 1193–1197 (1984).

[5] J. C. Piquette and A. L. Van Buren, "Nonlinear scattering of acoustic waves by vibrating surfaces," J. Acoust. Soc. Am. 76, 880–889 (1984).

[6] J. C. Piquette, "Nonlinear scattering of acoustic waves by vibrating obstacles," Ph.D. thesis, Stevens Institute of Technology, Hoboken, NJ (1983). (Also published as Naval Research Laboratory Memorandum Report No. 5077, Washington, DC, 1 June 1983.)

[7] See, e.g., R. T. Beyer, *Physical Acoustics*, edited by W. P. Mason (Academic, New York, 1965), Vol. II, part B, p. 234.

[8] P. H. Rogers, "Comments on 'Scattering by time varying obstacles,' " J. Sound Vib. 28, 764–768 (1973).

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Block 5. Monitoring Organization Report Number(s): Enter the unique alphanumeric report number(s) assigned by the Monitoring Agency. This should be a number assigned by a DoD or other government agency and should be in accordance with ANSI STD 239.23-74. If the Monitoring Agency is the same as the Performing Organization, enter the report number in Block 4 and leave Block 5 blank.

Block 6a. Name of Performing Organization: For in-house reports, enter the name of the performing activity. For reports prepared under contract or grant, enter the contractor or the grantee who generated the report and identify the appropriate corporate division, school, laboratory, etc., of the author.

Block 6b. Office Symbol: Enter the office symbol of the Performing Oganization.

Block 6c. Address: Enter the address of the Performing Organization. List city, state, and ZIP code.

Block 7a. Name of Monitoring Organization: This is the agency responsible for administering or monitoring a project, contract, or grant. If the monitor is also the Performing Organization, leave Block 7a. blank. In the case of joint sponsorship, the Monitoring Organization is determined by advance agreement. It can be either an office, a group, or a committee representing more than one activity, service, or agency.

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Block 8a. Name of Funding/Sponsoring Organization: Enter the full official name of the organization under whose immediate funding the document was generated, whether the work was done in-house or by contract. If the Monitoring Organization is the same as the Funding Organization, leave 8a blank.

Block 8b. Office Symbol: Enter the office symbol of the Funding/Sponsoring Organization.

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